Chapter 4
Mixture Proportioning Considerations

4-1. Selection of Concrete Mixture Proportions

The selection of concrete mixture proportions is an important step in obtaining economical, durable concrete meeting design requirements. Depending on the types of structures, the concrete mixture proportions may be selected by the Government or by the Contractor. When mixture proportions are to be selected by the Government, the work will be accomplished by a division laboratory. Proportions for mass concrete or structural concrete are to be selected in accordance with ACI 211.1 (CRD-C 99) and other criteria as described in the following paragraphs of this chapter whether the work is done by the Government or the Contractor. Any new materials proposed for use after the initial mixture proportioning studies must be proportioned by the division laboratory or the Contractor's commercial laboratory using actual project materials in a new mixture proportioning study.

4-2. Basis for Selection of Proportions

a. General. The process of selecting concrete mixture proportions is a process of optimization of several desirable characteristics based on the project requirements. The characteristics to be optimized are economy, strength, durability, and placeability.

b. Economy. The primary reason for systematically determining mixture proportions is economy. The maximum economy can be achieved by minimizing the amount of cement used and where appropriate, by replacing portland cement with usually less expensive pozzolan or GGBF slag. Economy is also improved by using the largest nominal maximum size aggregate consistent with the dimensional requirements of the structures on the project, and available to the project.

c. Strength. Strength is an important characteristic of concrete but other characteristics such as durability, permeability, and wear resistance may be equally or more important. These may be related to strength in a general way but are also dependent on other factors. For a given set of materials, strength is inversely proportional to the w/c. Since the materials which make up concrete are complex and variable, an accurate prediction of strength cannot be based solely on the selected w/c but must be confirmed by tests of cylinders made from trial batches with the materials to be used on the project. Strength at the age of 28 days is frequently used as a parameter for structural design, concrete proportioning, and evaluation of concrete. When mass concrete is used, the design strength is generally required at an age greater than 28 days, generally 90 days, because mixtures are proportioned with relatively large quantities of pozzolan or GGBF slag to reduce internal heat generation. The early strength of mass concrete will be low compared to that of structural concrete; therefore, mass concrete should be proportioned for an adequate early strength as may be necessary for form removal and form anchorage. A compressive strength of 500 psi at 3 days age is typical of that necessary to meet form-removal and form-anchorage requirements.

d. Durability. Concrete must resist deterioration by the environment to which it is exposed, including freezing and thawing, wetting and drying, chemical attack, and abrasion. Concrete must meet three requirements before it may be considered immune to frost action. It must be made with nonfrost-susceptible aggregates and a proper air-void system, and it must achieve an appropriate degree of maturity before repeated freezing and thawing is allowed to take place while the concrete is critically saturated. A proper air-void system is achieved by using an AEA. All exposed concrete placed by the Corps should be air entrained unless it is shown to be improper for a specific situation. The appropriate maturity exists when the concrete has a compressive strength of approximately 3,500 psi. Generally, durability is also improved by the use of a low w/c since this reduces permeability and the penetration of aggressive liquids.

e. Placeability. Placeability, including satisfactory finishing characteristics, encompasses traits described by the terms "workability" and "consistency." Workability is that property of freshly mixed concrete which determines the ease and homogeneity with which it can be mixed, placed, consolidated, and finished. Consistency is the relative mobility or ability of freshly mixed concrete to flow. Workability embodies such concepts as moldability, cohesiveness, and compactability and is affected by the grading, particle shape, and proportions of aggregate; the quantities and qualities of cementitious materials used; the presence or absence of entrained air and chemical admixtures; and the consistency of the mixture. The slump test, ASTM C 143 (CRD-C 5), is the only test commonly available to measure any aspect of the several characteristics included in the term "placeability." Moldability, cohesiveness, compactability, and finishability are mostly evaluated by visual observation, and, therefore, the evaluations are somewhat subjective. Typically, the Contractor will evaluate these characteristics from a different perspective than the government personnel involved, and within the Contractor's organization, the placing foreman may evaluate the placeability differently than the finishing foreman. In general, the Contractor would like a high-slump mixture, while the Government desires a closely controlled slump. The key consideration must be a carefully proportioned concrete mixture which is placeable by the conveying and placing equipment to be used on the project without the addition of water at the placement site. Simply adjusting the water content of a mixture that was proportioned for placement by crane and bucket will not assure that it is pumpable or that such an adjustment will result in concrete that meets strength and durability requirements. Mass concrete mixtures are particularly susceptible to placing problems if not correctly proportioned. Care must be exercised to assure that the mortar content of lean, mass concrete mixtures is sufficient to provide suitable placing and workability. Water-reducing admixtures should not be used to reduce the paste content and the resulting mortar content of these mixtures to a level which causes the mixture to be harsh and unworkable.

4-3. Criteria for Mixture Proportioning

a. General. The criteria for proportioning should be determined by the designer based upon the design and exposure requirements and conditions for the structure involved. Several sets of mixture proportioning criteria may be required for each structure to meet different design requirements. These criteria should be transmitted to the resident office as outlined in paragraph 6-2, "Engineering Considerations and Instructions for Construction Field Personnel."

b. Proportioning criteria.

(1) Maximum permissible w/c. The w/c of both structural and mass concrete should satisfy the requirements of Table 4-1.

(2) Structural concrete. For each portion of the structure, proportions should be selected so that the maximum permitted w/c is not exceeded and to produce an initial average compressive strength, f_{cr}, exceeding the specified compressive strength, f'_c, by the amount required. Where a concrete production facility has test records, a standard deviation shall be established. Test records from which a standard deviation is calculated:

• Shall represent materials, quality control procedures, conditions similar to those expected and changes in materials, and proportions within the test records shall not have been more restricted than those for the proposed work.

• Shall represent concrete produced to meet a specified strength or strengths f'_c within 1,000 psi of that specified for the proposed work.

• Shall consist of at least 30 consecutive tests or two groups of consecutive tests totaling at least 30 tests.

A strength test should be the average of the strengths of two cylinders made from the same sample of concrete and tested at 28 days or at some other test age designated. See ACI 318 for a more detailed discussion.

(a) Required average compressive strength f_{cr} used as the basis for selection of concrete proportions shall be the larger of the following equations using the standard deviation as determined in paragraph 4-3b(2):

$$f_{cr} = f'_c + 1.34s$$

$$f_{cr} = f'_c + 2.33s - 500$$

where s = standard deviation

(b) Where a concrete production facility does not have enough test records meeting the requirements above, a standard deviation may be established as the product of the calculated standard deviation and a modification factor from Table 4-2.

(c) When a concrete production facility does not have field strength test records for calculation of standard deviation, the required average strength f_{cr} shall be determined from Table 4-3.

(d) Evaluation and acceptance of concrete. The strength of the concrete will be considered satisfactory so long as the average of all sets of three consecutive test results equal or exceed the required specified strength f'_c and no individual test result falls below the specified strength f'_c by more than 500 psi. If the above criteria are not met, the resident engineer will notify the designer immediately so that the impact of the low strength may be evaluated. A "test" is the average of two companion cylinders, or if only one test cylinder is made, then a "test" is the strength of the one cylinder.

(3) Mass concrete. For mass concrete, the proportions selected for each quality of concrete for the project shall not exceed the maximum permitted w/c. Although there is typically a strength requirement for mass concrete, e.g. 2,000 psi at 1 year, the maximum-permitted w/c for

Table 4-1
Maximum Permissible Water-Cement Ratio (Notes 1 and 2)

Water-Cement Ratios by Mass (for Concrete Containing Cementitious Materials Other Than 100% Portland Cement, See Note 3)

	Severe or Moderate Climate (Note 4)		Mild Climate, Little Snow/Frost (Note 4)	
Location of Structure	Thin Section (Note 5)	Mass Section	Thin Section (Note 5)	Mass Section
At the water line in hydraulic or waterfront structures where intermittent saturation is possible (includes upstream face of dams, downstream face in overflow sections on dam where spillage occurs once per year or more often, and exposed surfaces of lock walls)	0.45	0.50	0.55	0.60
Interior of dams and lock walls and interior of other large gravity structures where use of two classes of concrete is practical	--	0.80	--	0.80
Ordinary exposed structures, downstream face of nonoverflow section of dams, downstream face in overflow section where frequency of overflow is less than once per year.	0.60	0.60	0.60	0.65
Complete continuous submergence in water after placement "in the dry" (includes upstream face of dams below minimum pool elevation)	0.60	0.65	0.60	0.65
Concrete deposited in water	0.45	0.45	0.45	0.45
Pavement slabs on ground:				
Wearing slabs	0.50	--	0.55	--
Base slabs	0.60	--	0.60	--
Exposure to sulfate ground water or other aggressive liquid or salt	0.45	0.45	0.45	0.45
Concrete subjected to high (more than 40 ft/s) velocity flow of water	0.45	0.45	0.45	0.45
Stilling basins (for flood control and other high-velocity flow structures)	0.45	0.45	0.45	0.45

Note 1. For all concrete placed in or exposed to seawater, the w/c should be reduced 0.05 below values shown in the table but not lower than 0.45.

Note 2. Mixtures should be proportioned by the division laboratory at the maximum specified slump and air content. They should also be proportioned at w/c's 0.02 less than the value shown in the table to allow for batching variability in the field.

Note 3. Where cementitious materials in addition to portland cement are used, the water-cementitious material ratio required is that which would be expected to give the same level of compressive strength at the time the concrete is exposed to the design environment as would be given by a mixture using no cementitious material other than portland cement.

Note 4. See Figure 4-1.

Note 5. Largest dimension is 12 in. or less.

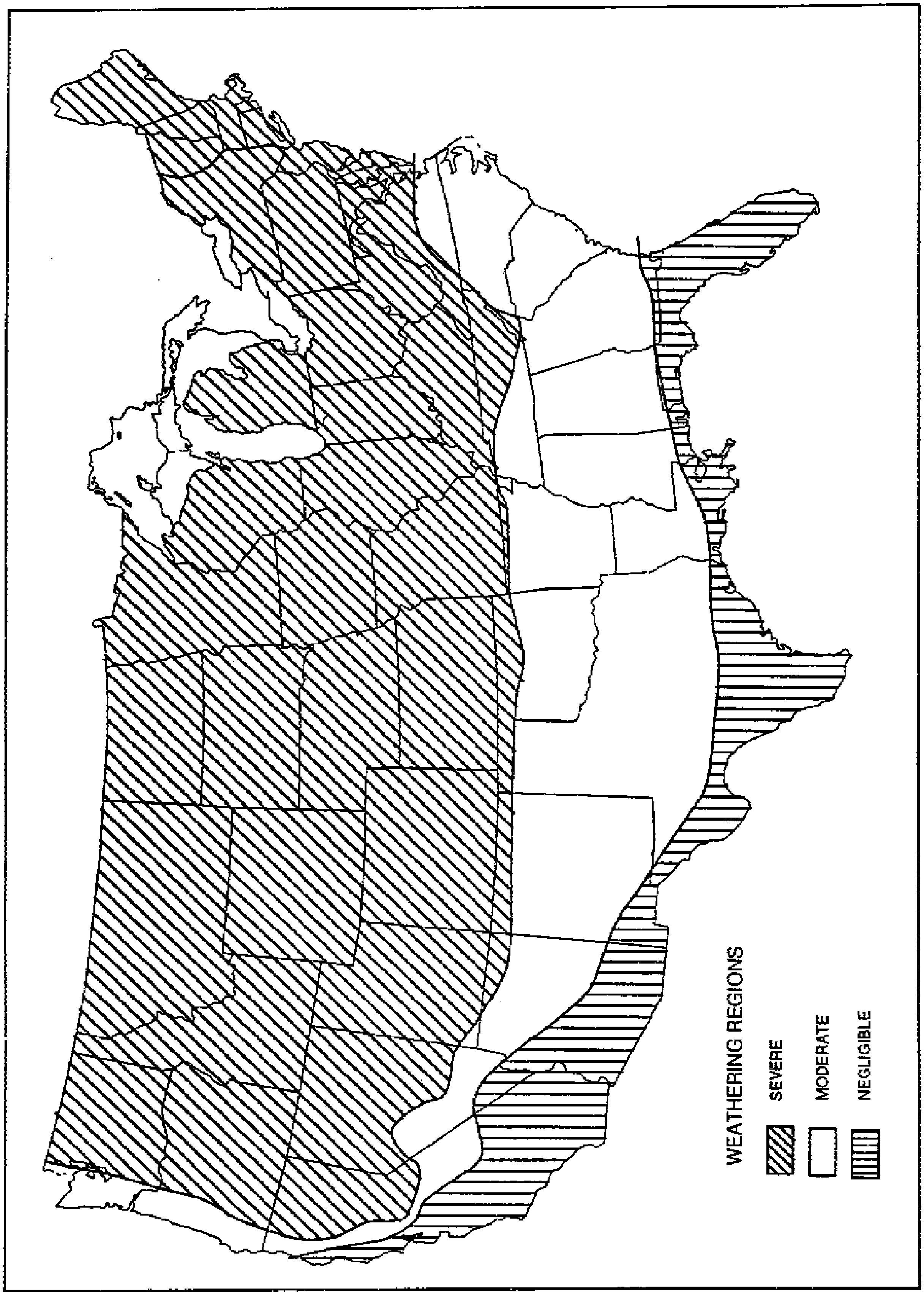

Figure 4-1. Location of weathering regions*

***Taken from Figure 1, ASTM C 33 (CRD-C 133).**

Table 4-2
Modification Factor for Standard Deviation

No. of Tests[1]	Modification Factor for Standard Deviation
Less than 15	See Table 4-3
15	1.16
20	1.08
25	1.03
30 or more	1.00

[1]Interpolate for intermediate numbers of tests.

Table 4-3
(See ACI 318, Table 5.3.2.2)

f'_c	f_{cr}
Less than 3,000 psi	$f'_c + 1{,}000$
3,000 - 5,000 psi	$f'_c + 1{,}200$
More than 5,000 psi	$f'_c + 1{,}400$

acceptable durability will often have a corresponding strength in excess of this value when the mixture meets the criteria in Table 4-1. Concrete that will be subjected to repeated freezing-and-thawing cycles while critically saturated with water must have developed a strength of about 3,500 psi before being allowed to freeze and thaw. If the maximum values in Table 4-1 are not low enough to ensure this strength under the anticipated environmental conditions and required duration of curing and protection, then the w/c (or water-cementitious material ratio) must be lowered or the required duration of curing and protection increased. To ensure that no more than 2 in 10 tests fall below the strength corresponding to the required w/c, the required average strength is determined as follows:

$$f_{cr} = f'_c + ts$$

where

t = 0.854 for 30 tests or less; 0.842 if more than 30 tests are available

s = standard deviation

Where results of fewer than 30 tests are available, the average strength should exceed f'_c by 600 psi. Mixtures will be proportioned to meet the required average strength except where the required w/c provides strength in excess of the design strength. The basis for the equation and the computation of standard deviation is found in ACI 214.

(4) Nominal maximum aggregate size. The nominal size of aggregate recommended for various types of construction is listed in Table 2-2.

(5) Water content. The water requirement is a function of the nominal maximum size aggregate, the aggregate grading, the required air content, and the required slump. Given these parameters, the approximate starting

water content for mixture proportioning studies can be determined from Table 6.3.3 of ACI 211.1. In the range of normal concretes, a given combination of aggregates requires an approximately constant amount of water per cubic yard of concrete for a given slump regardless of the w/c. In mass concrete, the water requirement is maintained low by the use of a large nominal maximum aggregate size and by the close control of grading.

(6) Cement content. The quantity of cementitious materials will be determined based on the maximum w/c and the estimated water requirement selected for the portion of the structure involved. In mass concrete, the usual low water requirement results in a low cement requirement which is one of the means of reducing the amount of heat developed by hydration.

(7) Proportioning with pozzolans or GGBF slag. Major economic and temperature rise benefits are derived from the use of pozzolans, blended cement, or GGBF slag. Therefore, concrete should be proportioned with the maximum amount of these materials that will satisfy the structural, durability, and other technical requirements as appropriate and be economically beneficial. Use of pozzolans and GGBF slag in mass concrete provides a partial replacement of cement with a material which generally generates less heat at early ages. The effects of these materials on the properties of freshly mixed concrete vary with the type and fineness; the chemical, mineralogical, and physical characteristics of the material; the fineness and composition of the cement; the ratio of cement to pozzolan or GGBF slag; and the total mass of cementitious material used per unit volume of concrete. Often, it is found that the amount of mixing water required for a given concrete slump and workability is lower for mixtures containing pozzolans or GGBF slag than for those containing only portland cement. Air-entraining admixture needs may be reduced by up to approximately 20 percent or increased by over 60 percent depending on the characteristics of the pozzolan or slag. Therefore, it is important to evaluate the pozzolan or slag using representative material samples during the laboratory mixture proportioning study. The dosage rate of chemical admixtures should generally be based on the total amount of cementitious material in the mixture. The proportion of cement to pozzolan or GGBF slag depends on the strength desired at a given age, heat considerations, the physical and chemical characteristics of both cement and cement replacement material, and the cost of respective materials. As a safety precaution against the possibility of increased alkali-silica reaction in concrete containing small (pessimum) amounts of certain pozzolans, the quantities of fly ash and natural pozzolan used in concrete should not be less than 15 percent by mass of total cementitious material. ASTM Type I (PM) should not be specified because of the possibility that it would contain the pessimum amount of pozzolan. The selected replacement quantities should be discussed in the concrete materials DM. This guidance will then be used by the division laboratory to proportion project concrete mixtures using materials submitted by the Contractor. Due to differences in their densities, a given mass of pozzolan or slag will not occupy the same volume as an equal mass of portland cement. The determination of w/c, by absolute volume equivalency, when pozzolan or slag is used is described in ACI 211.1.

4-4. Government Mixture Proportions

a. General. When concrete is being placed in a structure requiring the use of the guide specification for mass concrete, CW-03305, the mixture proportions are determined at a division laboratory using materials provided by the Contractor which are representative of those to be used in the project. Those division laboratories authorized to test concrete materials are listed in ER 1110-1-8100, "Laboratory Investigations and Materials Testing." Proportions for mass concrete or structural concrete are to be selected in accordance with ACI 211.1 and other criteria as described in the following paragraphs of this chapter.

b. Coordination between project, district design personnel, and the division laboratory. The criteria for proportioning the concrete mixtures to meet the requirement of each type of concrete required in a project is provided to the project personnel in detail in paragraph 6-2, "Engineering Considerations and Instructions for Field Personnel." The project personnel should notify the division laboratory of the required proportioning criteria at the time that the samples are transmitted from the Contractor to the laboratory. Much time is lost when several tons of aggregate and cement are delivered with no previous notification by Corps project personnel that the material was coming and no indication of proportioning criteria required. Since the specification indicates when the Contractor should expect starting mixtures after he submits his materials samples, close coordination between the Corps personnel on the project and in the division laboratory is essential, not only to assure that mixture proportions meet the project needs but also to avoid delay claims by the Contractor. The "Guide Specification for Mass Concrete," CW-03305, requires the designer or specification writer to state the number of days prior to the start of concrete placing that materials for mixture proportioning studies must be submitted to the division laboratory. Timely submittal of these materials is the responsibility of the project office.

c. Sampling of materials. Guide Specification CW-03305 outlines the procedure by which samples are to be taken by the Contractor for mixture-proportioning studies. The Contractor is required to test the aggregates for quality and grading before shipment to the laboratory. These samples are to be taken under the supervision of the Contracting Officer. It is important that this requirement is followed. The most common problems arising from lack of attention to these details are samples arriving at the division laboratory which do not meet project grading requirements or are not representative of the materials that are actually to be used or both. Both problems may lead to delays of concrete placements or the necessity for considerable field modification of the mixture proportions. The division laboratory should test submitted materials to determine that they meet specification requirements prior to using them to develop mixture proportions. The need for the samples that are submitted to be representative extends to all the materials in the concrete, including cement, pozzolans, GGBF slag, and chemical admixtures.

d. Data supplied by division laboratory to project. For each type of concrete required on the project, the division laboratory should select initial proportions that satisfy the mixture criteria provided by the project personnel. The batch amounts of each constituent in a cubic yard should be reported in the saturated-surface dry (SSD) condition. The amounts of chemical admixtures such as air-entraining and water-reducing admixtures will be reported as fluid ounces per 100 lb of cementitious materials. Strength data will be provided for each type of concrete to the extent that it is available by the time the proportions are transmitted to the project. As a minimum, 24-hour, 7-day, 28-day, and design-age strengths should be available prior to the start of placement. A regression analysis of accelerated strength at a later age should be computed to determine the correlation coefficient and 95 percent confidence limits (see ACI 214.1R). The mixture proportions provided for each type of concrete should include a family of curves of strength versus water-cementitious materials ratio at various ages.

e. Adjustment of government mixture proportions. The mixture proportions provided by the division laboratory provide starting mixtures meeting the project criteria. However, when these proportions are used in the first batches of concrete produced by the Contractor's plant, it is not uncommon for the concrete to be deficient in one or more of the control parameters of the specifications. The most common deficiency is in the slump. The laboratory will report mixture proportions based on the aggregates in an SSD condition. A common cause of an increase in slump is the failure to properly adjust for free moisture in the aggregate, particularly the fine aggregate. Low slump is normally not a problem if concrete is batched and mixed on site unless rapid slump loss occurs. Variations in the chemical or physical properties of cement or pozzolan are the most common causes of rapid slump loss although transporting and placing operations may also contribute to the problem. Assuming all materials and transporting and placing equipment and operations meet specification requirements, the most practical solution for dealing with rapid slump loss is to increase the slump at the mixer to the degree necessary to have a slump at the forms which is within the specification limits. The w/c should be maintained constant if the slump is increased. Care should be taken to determine if the addition of cementitious materials necessary to maintain a constant w/c will detrimentally affect the thermal properties of the concrete or nullify results of a thermal stress analysis. Adjustments of the dosage of air-entraining admixture by the Contractor are required as needed to maintain air contents within the specified range. As gradings of individual coarse aggregate size groups change, the proportions of the size groups should be adjusted so that the combined coarse aggregate grading approximates the maximum density grading. The maximum density grading may be computed using Equation A5.3 in ACI 211.1. As the combined coarse aggregate grading approaches the maximum density grading, the void content of the mixture is reduced and more mortar is available for placeability, workability, and finishability. Solution of the percentage of each size group can usually be done such that the combined coarse aggregate grading is generally within 2 or 3 percent of the maximum density grading. Trial and error may be used in selecting the percentage of each size group necessary to produce a combined coarse aggregate grading which approximates the maximum density grading; however, proprietary computer programs are also available. Contact CECW-EG for the available computer programs. Adjustments in the percentage of fine aggregate is less common, but slight changes may be necessary to compensate for significant changes in grading over an extended period of production. Adjustments to government mixture proportions are to be made by government personnel. Changes in aggregate and water batch weights to compensate for free moisture in aggregates are made by the Contractor and are not considered adjustments to mixture proportions. Division laboratory personnel should be present and prepared to make adjustments in mixture proportions when the Contractor initiates concrete production on a project and after periods of batch plant shutdown such as winter shutdowns or prolonged strikes. Procedures for making adjustments are given in ACI 211.1 and will be made on an absolute volume basis. The mortar volume should remain constant and changes in any one mortar constituent such as water, fine aggregate, air, or cementitious material content should be compensated for by changes in another mortar constituent without changing the w/c. It is important that adjustments to the government mixture proportions be made during plant shake-down, before any concrete is placed in the structure.

4-5. Evaluation of Contractor-Developed Mixture Proportions

a. General. The Contractor should submit his mixture proportions for review prior to initiating concrete placement. The mixture proportions should be developed in accordance with ACI 211.1.

b. Reviewing contractor submittals.

(1) Minor structures. When the concrete being placed is in a minor structure, the concrete will almost always be supplied by a ready-mixed concrete producer. The mixture proportions will normally be submitted as a tear sheet from the producer's catalog or as a data sheet from a local commercial laboratory which was retained at some time to prepare a series of mixtures for the producer to market. Review of these submittals should include a determination that the type of cement used, the air-entraining admixture, and the aggregate source are the same as will be used on the project and that each constituent meets the specification requirements. Test cylinder data submitted by the Contractor should not be more than 180 days old. The w/c, f'_c, and f_{cr} must satisfy the contract requirements.

(2) Cast-in-place structural concrete. Because the structures for which this guide specification is applicable are important structures involving water control and power production, the specification requirements provided to the Contractor for proportioning the concrete mixtures are similar to those followed by the division laboratory when the Government is required to proportion the mixture. The review of the submitted mixture proportions should assure the following:

(a) Cementitious materials. The submitted mixture must be proportioned using the same cementitious materials as will be used in the project. This should include type, manufacturer, mill of origin, and time of manufacture. If a pozzolan is to be used, the Contractor's submittal should state whether the percentage of replacement is based on mass or volume.

(b) Aggregate. The aggregate used in proportioning the mixture should represent the current production of whichever source the Contractor selects. Quality tests and grading test results should be submitted showing that the aggregates meet specification requirements. Batch amounts for aggregates should be listed in the SSD condition unless some other basis is agreed on.

(c) Admixtures. The admixtures used in proportioning the mixture should be from the same stock that the Contractor has purchased for use on the project or from the current stock of the ready-mix producer for the project. All admixtures should meet the project specifications and the dosages should be listed.

(d) Test results. The w/c and required strength test results should be reviewed to assure that they match project requirements. Air contents and slumps should be at the upper limits of the specification requirements.

(e) Placeability. The mixtures must be proportioned to provide the necessary placeability for the conveying and placing equipment that the Contractor proposes to use. For instance, concrete that will be pumped may be proportioned differently than concrete that will be delivered by crane and bucket, or directly from the truck mixer, or by tremie pipe, etc.